Classical and Quantum Computing modalities-A Review

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Abstract

Quantum computers generally need to operate under more regulated physical condition than classical computer because of quantum mechanics. Classical computer uses bits and quantum computer use qubits. According to IBM, "Groups of quits in superposition can create complex, multidimensional computational spaces" that enable more complex calculations. Quantum algorithms like Shor's and Grover's run significantly faster than various algorithms for classical computer. Quantum entanglement offers fascinating opportunities for enhancing AI algorithms through improved computational efficiency. But practical implementation remains challenging due to technical limitations and the need for further research in the field of quantum machine learning. This article provides a brief overview of different quantum computing methods.

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Introduction

While conventional or classical computing has been the foundation of technological advancements for decades, the emergence of quantum computing has sparked both curiosity and excitement [1,2]. To understand the importance of this shift from classical computing, it is essential to understand the fundamental differences between classical and quantum computer. Quantum computing exploits the principles of quantum mechanics (superposition, entanglement, and interference) to exploit the quantum behavior of elementary particles (qubits) to perform computations [3-5]. At the heart of quantum computing are quantum bits (qubits), which can exist in more than one state at once due to a phenomenon called superposition [6-7]. Unlike classical bits, which are limited to being either 0 or 1, quantum bits can represent both 0 and 1 simultaneously, allowing for a dramatic increase in computational power. By harnessing the properties of quantum bits such as superposition and entanglement, it is possible to increase the processing power of AI systems. This quantum-AI synergy could tackle computationally-intensive tasks beyond classical computers' reach, potentially helping to power breakthroughs in drug discovery, materials science, financial modeling and cryptography [8-9]. The difference between classical computer and quantum computer are like a horse and a hawk: a horse can run, and a hawk can fly [10-11]. Classical computers and quantum computers are truly different. Here we take a closer look at what the main differences are, what quantum computers are and how they work. This article explores these and other questions, taking into account the challenges ahead and the extreme temperatures required to operate the quantum computer.

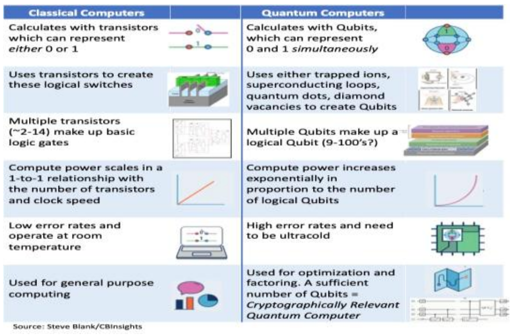

Figure 1: The difference between classical and quantum computer. Taken from Wikipedia.

The main methods of Quantum Computing are:

Superconducting quantum computing: This method uses superconducting circuits operating at cryogenic temperatures. Superconducting qubits are made of materials that exhibit superconductivity, allowing the manipulation of quantum states at high speeds and low error rates.

Figure 2: Illustration of superconducting quantum qubits. Taken from Wikipedia.

The technology has been widely developed by companies such as IBM and Google, and is one of the most prominent approaches in the field [12].

Photonic Quantum Computing: Photonic quantum computers use photons (light particles) as qubits. They manipulate light through various optical components, such as beam splitters and phase shifters, to perform computations. This method benefits from room-temperature operation and scalability, which makes it suitable for large-scale quantum systems. Companies like Xanadu and Psi Quantum are exploring different techniques in this category, including squeezed light states [13-15].

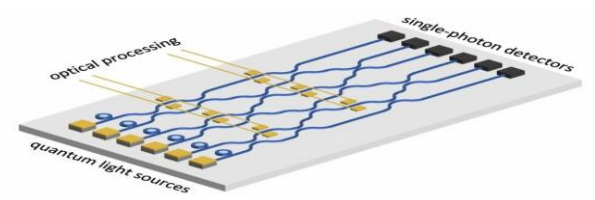

Figure 3: Diagram of photon qubits. Excerpt from Wikipedia.

Quantum Computing with Trapped Ion: In this approach, individual ions are trapped using electromagnetic fields and manipulated with laser beams to perform quantum operations. Trapped ions offer long coherence times and high computational precision, which are important for efficient quantum computing. This method has been successfully implemented by companies such as IonQ and Honeywell [16-18].

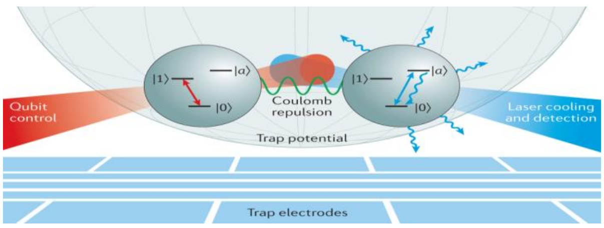

Figure 4: Illustration of trapped ion quantum qubits. Taken from Wikipedia.

Neutral Atom Quantum Computing: Neutral atom technology involves trapping neutral atoms using optical tweezers (focused laser beams). This method is less sensitive to electric fields compared to trapped ion systems, allowing for more robust operations. Neutral atom systems can operate at higher temperatures, which simplifies certain aspects of their implementation [19].

Figure 5: Illustration of quantum qubits of the neural atom. From Wikipedia.

Quantum Dots: Quantum dots are semiconductor particles that confine electrons in three dimensions. This is an emerging field that uses silicon, a material essential to classical computing, to create qubits— the basic units of quantum information. Recent advances aim to improve the purity and scalability of silicon qubits, making them a promising candidate for future quantum computers. However, challenges remain in achieving long coherence times [20-23].

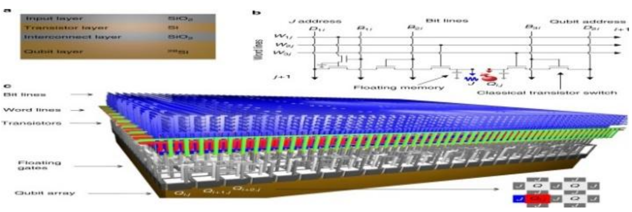

Figure 6: Diagram of quantum dot qubits. Quoted from Wikipedia.

Hybrid Quantum Computing: Hybrid systems combine classical computing elements with quantum processors to leverage the strengths of both technologies. This approach can optimize certain computations by using a combination of classical and quantum algorithms [24-25].

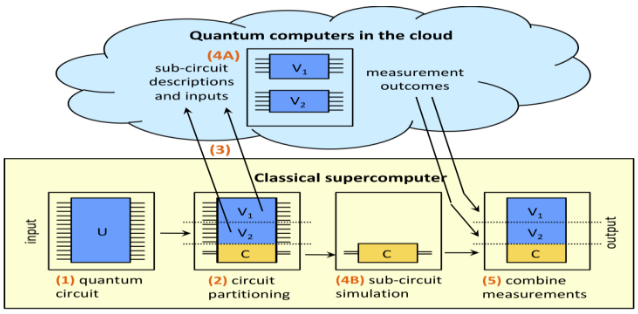

Figure 7: Fig. of hybrid quantum calculation. Taken from Wikipedia.

Carbon-based Quantum Computing: This new technology uses carbon nanotubes combined with quantum dots to create qubits that have the advantage of long coherence times and reduced error rates in noisy environments. The mechanical oscillators formed by these structures could improve performance in practical applications [26].

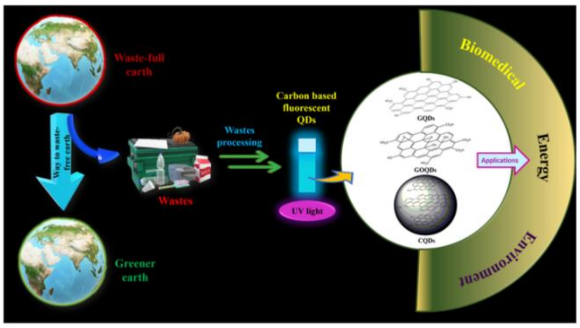

Figure 8: Illustration of quantum calculations based on carbon. Taken from Wikipedia.

Cold Atom Quantum Computing: The use of cold atoms to form qubits is a cutting-edge research area in quantum computing that exploits the unique properties of ultracold atomic systems to create and manipulate quantum bits (qubits). The process typically involves cooling atoms to extremely low temperatures and trapping them using laser technology [27].

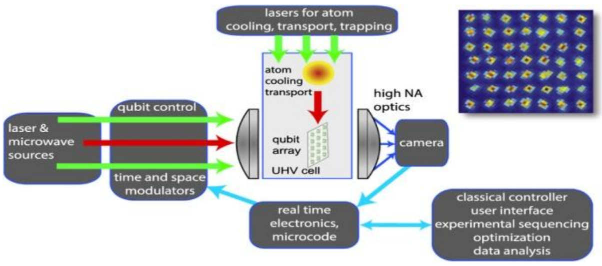

Figure 9: Diagram of quantum computing on cold atoms. Quoted from Wikipedia.

NV centres for Quantum Computing: NV (Nitrogen-vacancy) centres in diamond are increasingly attracting attention as a promising platform for quantum computing due to their unique properties and capabilities. These centres exploit defects in diamond crystals, specifically the combination of nitrogen atoms and vacancies, to create quantum bits that can operate efficiently at room temperature [28].

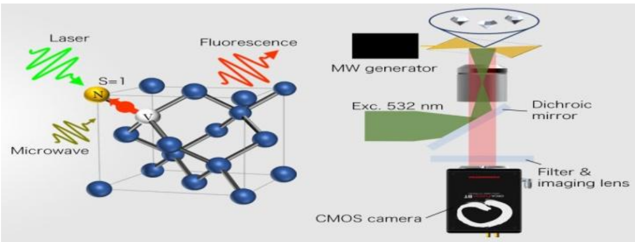

Figure 10: Illustration of NV centre Quantum boxes. Taken from Wikipedia.

Majorana Quantum Computing: Majorana fermions, theoretically proposed by Ettore Majorana in 1937, are a single particle that is its own antiparticles. These special properties make them promising candidates for advancing quantum computing technology, especially in the development of topological quantum computers. These computers leverage the stability and fault tolerance provided by Majorana fermions to address some of the significant challenges faced in quantum computing [29-31].

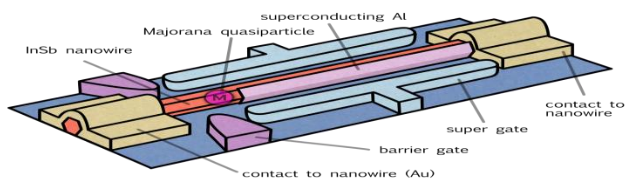

Figure 11: Diagram of Majorana quantum computing. Taken from Wikipedia.

Practical applications

Quantum computers have the potential to revolutionize data processing in many areas, from **cryptography** to the **simulation of complex systems** [32,34,36]. Below are most promising applications of quantum computer:

Figure 12: Need of quantum computer. Taken from Wikipedia.

Quantum cryptography: Quantum encryption uses quantum characteristics to protect communication from eavesdropping. Quantum computers can generate secure cryptographic keys more efficiently than classical computers and can break some of the encryption techniques commonly used today.

Optimization: Quantum Computer can solve optimization problems much more efficiently than classical computers. This makes it suitable for solving complex problems such as vehicle route planning and resource allocation.

Quantum Simulation: Simulating quantum systems is an extremely challenging task for classical computers. On the other hand, quantum computers can simulate the dynamics of quantum systems such as molecules and materials, opening up new possibilities for the discovery of new materials and drugs.

Quantum machine learning: Machine learning is one of the most promising application areas for quantum computer. Quantum computer can take advantage of quantum superposition to perform simultaneous learning operations on many possible solutions, making training of **machine learning** models more efficient.

Finance: Quantum computers can be used to analyze large amounts of financial **data** and predict market prices more efficiently than classical computers.

Future challenges for quantum computers

Despite progress toward the realization of quantum computers, many problems still need to be solved before quantum computer can be widely used [33,35,37]. Below are some of the most important tasks of these computers:

Stability and error reduction: Quantum computers are prone to errors due to factors such as environmental noise and qubit instability. For quantum computers to be useful in real world applications, new ways to reduce errors and improve stability need to be developed.

Scalability: Currently, the most advanced quantum computers contain only a few dozen qubits, but to solve really complex problems, many more qubits are needed. Therefore, in order to promote this technology, it is essential to develop technology to increase the number of qubits and improve the scalability of quantum computers.

Control and management: Qubit management is complicated and requires special techniques. Moreover, controlling and reading qubits requires highly sophisticated laboratory equipment and methods. For quantum computers to be useful in real world applications, new ways to simplify the managing and controlling of qubits must be developed.

Algorithms: Not all problems are suitable for quantum computers. New algorithms must be developed that are specifically designed to exploit the unique properties of quantum computers and solve complex problems.

Standardization: Quantum computers are produced by different companies and use different methods and protocols. It is required to develop common methods and protocols to ensure correlation between the various systems and make it easier for the people working in this field to use these machines.

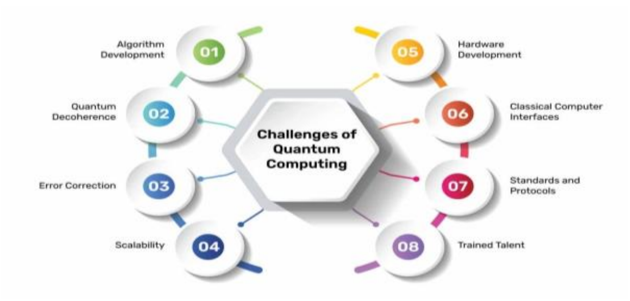

Figure 13: Challenges of quantum computing. Excerpt from Wikipedia.

Conclusion and Future Prospective

In conclusion, each method of quantum computing has its own set of advantages and challenges, making the field diverse and dynamic. The current research and development in this field aim to improve these unique strengths while diminishing the weaknesses. The main goal is to build reliable quantum computers that can solve problems that cannot be solved by classical machines. As research progresses, these technologies may converge or evolve further, potentially leading to breakthroughs in computational power and efficiency across various applications. Both classical and quantum computing have their unique strengths and weaknesses. Classical computing is necessary for day-to-day applications. With new advancements, we welcome new technologies every day, and one such breakthrough in technology is quantum computers. Despite the fact that people have reached a milestone and have invented very fast supercomputers, there are still specific tasks unhandled by these computers, such as calculations of the prime factors of very large integers. Quantum Computers are far ahead of classical computers and will soon become our very powerful companions in the future.

References

1. A Steane, "*Quantum computing*", Reports on Progress in Physics, 61:117-173, 1998.
2. B M Terhal, "*Quantum supremacy, here we come*", Nature Physics, 14: 530-531, 2018.
3. H D Zeh, "*Feynman's interpretation of quantum theory*", The European Physical Journal H, 36:63-74, 2011.
4. P W Shor, *"Polynomial-time algorithms for prime factorization and discrete logarithms on a quantum computer"*, SIAM review, 41: 303-332, 1999.
5. S Aaronson and Ambainis, A Forrelation, *"A problem that optimally separates quantum from classical computing"*, In Proceedings of the forty-seventh annual ACM symposium on Theory of computing, pages 307–316, 2015.
6. J Anandan and Y Aharonov, *"Geometry of quantum evolution"*, Physical review letters, 65:1697-1700, 1990.
7. L. Gurvits, *"Classical complexity and quantum entanglement"*, Journal of Computer and System Sciences, 69: 448–484, 2004.
8. B Lu, M Lin, Y Shu et al., *"Approximation of the nearest classical state to a quantum state"*, arXiv preprint arXiv:2301.09316, 2023.
9. B W Reichardt, F Unger, and U. Vazirani, *"Classical command of quantum systems"*, Nature, 496: 456–460, 2013.
10. C M Unsal and A Yavuz Oruc, *"Faster quantum concentration via grover's search"*, International Journal of Parallel, Emergent and Distributed Systems, pages 1–16, 2023.
11. I L Chuang, N Gershenfeld, and M Kubinec, *"Experimental implementation of fast quantum searching"*, Physical Review Letters, 80: 3408–3411, 1998.
12. H L Huang, D C Wu, D J Fan, et al, *"Superconducting Quantum Computing: A Review"*, Science China Information Sciences, 63: 180501, 2020.
13. N Maring, A Fyrillas, M Pont. *et al*, *"A versatile single-photon-based quantum computing platform"*, Nat. Photon,18: 603–609, 2024.
14. H S Zhong, *et al*, *"Quantum computational*

advantage using photons", Science, 370: 1460–1463, 2020.
15. P Michler, A Imamoglu, M D Mason, P J Carson, G F Strouse, and S K Buratto, *"Quantum correlation among photons from a single quantum dot at room temperature"*, Nature (London), 406:968, 2000.
16. Colin D. Bruzewicz, John Chiaverini, Robert McConnell, Jeremy M. Sage, *"Trapped-ion quantum computing: Progress and challenges"*, Appl. Phys. Rev., 6: 021314, 2019.
17. L Zhao *et al*, *"Orbital-optimized pair-correlated electron simulations on trapped-ion quantum computers"*, npj Quantum Inf., 9: 60, 2023.
18. J J Cirac and P Zoller, *"Quantum computations with cold trapped ions"*, Physical Review Letters, 74:4091–4094, 1995.
19. N Jain, B Coyle, E Kashefi, & N Kumar, *"Graph neural network initialization of quantum approximate optimization"*, Quantum, 6: 861, 2022.
20. D Loss and D P DiVincenzo, *"Quantum computation with quantum dots"*, Physical Review A, 57:120–126, 1998.
21. T Calarco, A Datta, P Fedichev, E Pazy, and P Zoller, *"Spin-based all-optical quantum computation with quantum dots: Understanding and suppressing decoherence"*, Physical Review A, 68:012310, 2003.
22. A Skinner, M Davenport, and B Kane, *"Hydrogenic spin quantum computing in silicon: A digital approach"*, Physical Review Letters, 90:087901–087905, 2003.
23. D Copsey, M Oskin, F Impens, T Metodiev, *"A Cross, F Chong, and J Chuang Kubiatowicz. Toward a scalable, silicon-based quantum computing architecture"*, Journal of Selected Topics in Quantum Electronics, 9:1552–1569, 2003.
24. W Li, Z Yin, X Li et al., *"A hybrid quantum computing pipeline for real world drug discovery"*, Sci Rep, 14: 16942, 2024.
25. A Gircha, A Boev, K Avchaciov, P Fedichev & A Fedorov, *"Hybrid quantum-classical machine learning for generative chemistry and drug design"*, Sci. Rep., 13: 8250, 2023.
26. A G Bracamonte, *"Quantum Semiconductors Based on Carbon Materials for Nanophotonics and Photonics Applications by Electron Shuttle and Near Field Phenomena"*, Recent Progress in Materials, 5:03, 2023.
27. Meng Ye, Ye Tian, Jian Lin, Yuchen Luo, Jiaqi You, Jiazhong Hu, Wenjun Zhang, Wenlan Chen, and Xiaopeng Li., *"Universal Quantum Optimization with Cold Atoms in an Optical Cavity"*, Phys. Rev. Lett., 131: 103601, 2023.
28. M W Doherty et al., *"Theory of the ground-state spin of the NV^- center in diamond"*, Phys. Rev. B, 85: 205023, 2012.
29. Q L He, et al., *"Chiral Majorana fermion modes in a quantum anomalous Hall insulator superconductor structure"*, Science, 357: 294–299, 2017.
30. AY Kitaev, *"Unpaired Majorana fermions in quantum wires"*, Phys-Usp, 44: 131–136, 2001.
31. D Aasen, et al., *"Milestones toward Majorana-based quantum computing"*, Phys Rev X, 6: 031016, 2016.
32. M Mohseni, P Read, H Neven et al., *"Commercialize quantum technologies in five years"*, Nature, 543: 171-174, 2017.
33. S Aaronson. *"Ten semi-grand challenges for quantum computing theory"*, 2005.
34. S Aaronson and A Ambainis, *"The need for structure in quantum speedups. Theory of Computing"*, 10: 133–166, 2014.
35. C Outeiral *et al.*, *"The prospects of quantum computing in computational molecular biology"*, Wiley Interdiscip. Rev. Comput. Mol. Sci., 11: e1481, 2021.
36. R Santagati et al., *"Drug design on quantum computers"*, Nat. Phys., 20: 549–557, 2024.
37. N S Blunt *et al.*, *"Perspective on the current state-of-the-art of quantum computing for drug discovery applications"*, J. Chem. Theory Comput., 18: 7001–7023, 2022.